Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering

doi:10.3233/978-1-61499-656-9-2733

The influence of earth temperature on dynamic characteristics of frozen soil and the parameters of ground motion at the sites of permafrost in the Qinghai-Tibet Plateau

L'influence des temperatures du sol sur les caracteristiques dynamiques des sols geles et les parametres de mouvements de sol sur les sites de neiges eternelles du Plateau Qinghai-Tibet

Lanmin Wang, Zhijian Wu & Dongli Zhang
Lanzhou Institute of Seismology, China Earthquake Administration, Lanzhou 730000, China
Luxin Zhang
Qinghai-Tibet Railway Company, Germold 817000, China

ABSTRACT
Based on the field investigation on the west of Kunlun mountain pass 8.1 earthquake in 2001 and site exploration along Qinghai-Tibet Railway in China, the influence of temperature on dynamic constitutive relationship, dynamic elastic modulus and dynamic strength of frozen soil were studied quantitatively by means of dynamic triaxial test. Moreover, the characteristics of ground motion on permafrost site under different earth temperatures were analyzed for the four profiles of permafrost along the Qinghai-Tibet railway using the time histories of ground motion acceleration with 3 exceedance probabilities for Kunlun mountain area. The results show that earth temperature has predominant influence on seismic displacement, velocity, acceleration and response spectrum on permafrost sites. A scientific basis was presented for earthquake disaster prevention of structures, railways, highways and underground engineering in permafrost areas.

RÉSUMÉ
D'après L'étude effectuée à l'owest du Mont Kunlun Concernant le tremblement de terre de 8.1 ayant lieu en 2001, ainsi que rexploration le long de la ligne de chemin de fer Qinghai-Tibet, en Chine, l'influence des températures sur les modèle élastique constitutives, les module élastique dynamique et la force dynamique de la terre gelée ont été quantitativement étudiées selon le test à trois axes dynamique. De plus, les caractéristiques des movements de sol sur les sites de neiges éternelles, sur différente tempèrature de sol ont été analyseés d'après les 4 types de neiges éternelles le long de la ligne de chemin de fer Qinghai-Tibet, Purcela, l'on a utilisé l'histoique de l'accélération des mouvements de sol avec 3 probabilités d'exceedance pour la zone du Mont Kunlun. Les résultats démontent que la température du sol a une influence prédominante sur les déplacements sismiques, la vitesse l'accélération et la gamme de répercussion . Des séismes sur les zones de neiges étenelles, une base scientifique a été présentée pour les mesure de prévention des tremblements de terre et leure répercussions sur les structures, voies ferrées, auto routes et Ťngiére souterraines dams les zones de neiges éternelles.

1 INTRODUCTION

The area of permafrost, seasonal frost and short-time frost on the earth is about 70% of the total area of the continents (Wang Shaoling, 1996). The area of permafrost in high elevation region in China is the largest in the world (Ma Wei, 1995). However, the Qinghai-Tibet plateau is a region with the largest permafrost area, the biggest depth and the lowest temperature, where is with the middle and low altitude of the north hemisphere. The north boundary of frozen soil area is at the north slope of Kunlun Mountain and the south limit is at the north slope of Himalayas. The area is about 1.5 million km^2, which is 70% of frozen soil areas in China (Tong Boliang, 1983). The Qinghai-Tibet Plateau is also one of high seismicity regions, where 14 Ms 6.0～6.9 earthquakes, 2 Ms 7.0～8.5 earthquakes have occurred since 1980. Especially the west of Kunlun mountain pass 8.1 earthquake on 14^{th} November, 2001 caused a large scale of ground failure in the permafrost region. It has caused certain extent of damage and potential hazard for infrastructure construction projects of in permafrost area of the Qinghai-Tibet Plateau related to the strategy of developing the western China. Therefore, it is very important and pressing to study earthquake disaster mitigation in the permafrost region on the Qinghai-Tibet Plateau.

The variety of earth temperature is one of the most important factors of influencing the mechanical property of frozen soil. However, that the laboratory research has only been started since the middle period of 1970s for static characteristics, strength and deformation under cyclic loading of frozen soil with different minus temperatures, textures and initial water content. The research data with regard to dynamic characteristics of frozen soil under seismic dynamic loading and the influence of temperature on it is very scarce (Wu Zhijian, 2003). Without disturbing caused by the outside factors and human engineering activities, permafrost has high seismic strength. But in the past tens of years, because of global warming, the average annual temperature in the Qinghai-Tibet plateau increased by 0.2～0.4℃, and the temperature increase is bigger in winter. The annual variation range of ground temperature decreasing gradually, furthermore, the air temperature in the plateau is predicted to increase by 2.2℃～2.6℃ in the future ten years. Thus, the degradation of permafrost is regional and consequently, the natural geographical, geological and engineering geological environment of permafrost area along Qinghai-Tibet Highway has changed greatly due to the environment change caused by global warming and degradation of permafrost (Wang Guoshang, 1996). Their influence on seismic performance of permafrost sites has two aspects: (1) the deformation of permafrost under seismic loading is usually much greater and very easy to fail; (2) the influence of the changes of dynamic characteristics of permafrost on ground motion parameters of a site will be very remarkable. Thus, it is very important in Civil Engineering terms to study the influence of temperature on dynamic characteristics of frozen soil and the parameters of ground motion on the permafrost site.

2 THE INFLUENCE OF EARTH TEMPERATURE ON DYNAMIC PARAMETERS OF FROZEN SOIL

The dynamic constitutive relationship, dynamic elastic modulus and dynamic damping ratio are the dynamic model and parameters for calculating the parameters of ground motion on permafrost sites and the parameters of dynamic strength, dynamic cohesion, C_d and dynamic friction angle, φ, are indexes of shear strength of soil. In order to investigate the changing pattern of the models and parameters with earth temperature variation, dynamic triaxial tests were performed on frozen soil samples with different temperatures of -10℃, -7℃, -5℃ and -2℃, by dynamic triaxial system of MTS-810 with the low-temperature apparatus at the State Key Laboratory of Frozen Soil Engineering.

2.1 *The influence of earth temperature on dynamic elastic module and damping ratio of frozen soil*

The results from laboratory indicate that the curve of dynamic stress versus dynamic strain of frozen soil with different temperatures can be described in a hyperbolic model of Hardin-Drnevich (Qian Jiahuan,1996) under cyclic sinusoidal loading (Fig. 1), which is shown as follows:

$$\sigma_d = \varepsilon_d / (a + b \times \varepsilon_d) \quad (1)$$

Where, σ_d is dynamic stress, ε_d is dynamic strain, *a* and *b* are coefficients obtained from the test. In the hyperbolic model of frozen soil under seismic dynamic loading, *a* and *b* are influenced predominantly by temperature of frozen soil. With the decrease of temperature, both of them will become smaller. When the temperature falls from -2℃ to -5℃, *a* and *b* will decrease obviously, where the maximum decreasing value of *a* is 0.832, and that of b is 0.077. However, when the temperature falls from -7℃ to -10℃, they don't decrease remarkably. The maximum decreasing value of *a* is 0.095 and that of *b* is 0.0194. At the same temperature, the module suggested by formula (1) fits well for the two groups of samples. This means that the test result has good repetition.

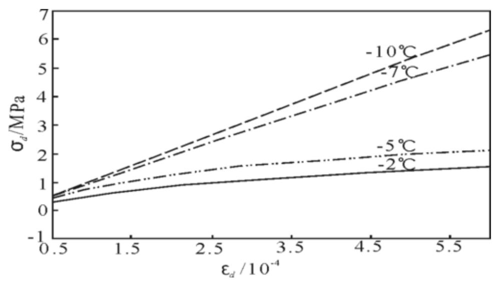

Figure 1. The curves of dynamic stress versus dynamic strain under different temperatures

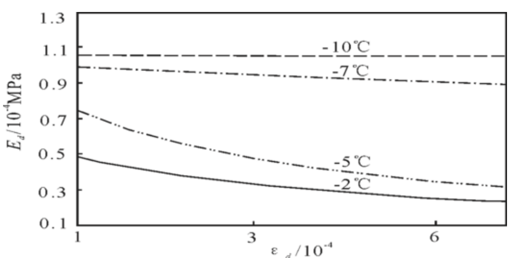

Figure 2. The curves of dynamic modulus versus dynamic strain under different temperatures

With the temperature decreasing, the dynamic elastic modulus increases, especially at the range of dramatic change from water phase to ice phase, which ranges from 0℃ to -5℃ in temperature, the change is more evident. With increasing of the dynamic strain, the dynamic elastic module of frozen soil decreases (Fig. 2). The reason of which is that the cementation and joint of ice in frozen soil are sensitive to the change of temperature.

2.2 *The influence of earth temperature on parameters of dynamic strength of frozen soil*

The dynamic strength curves based on tests under three different temperatures: -2℃, -5℃ and -7℃ are shown in Fig.3. They are the curves of dynamic shear stress ($\sigma_{1\max} - \sigma_{3c}$) versus cyclic times corresponding to the same failure criterion when total strain develops to 15%. Furthermore, the two parameters of dynamic shear strength , dynamic cohesion (C_d) and dynamic friction angle (φ_d), under dynamic loading can be got.

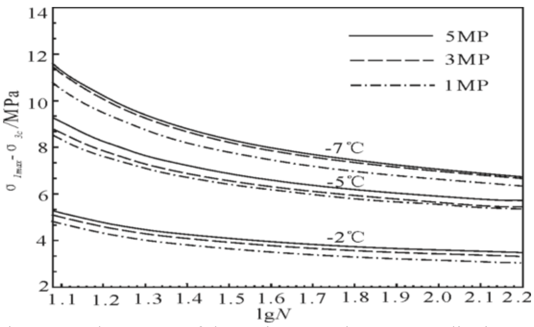

Figure 3. The curves of dynamic strength versus cyclic times under different temperatures and confining pressures

The dynamic cohesion may be described by formula (2). It is worthy to say that the dynamic cohesion is an important part in the total shear strength of frozen soil, especially the frozen soil with high temperature. For this reason, it is feasible that only dynamic cohesion is taken into account in many cases.

$$C_d = a + b \times (|T|)^{1/2} \quad (2)$$

Where, C_d is dynamic cohesion; *T* is negative temperature; *a* , *b* are coefficients from the tests.

Since the dynamic friction angle is very small (< 6°C), and it takes less proportion in the total shear strength, the influence of temperature on it is more distinct. When cyclic times are 20 and 30 respectively, the influencing of temperature can be described with the following formula (3).

$$\phi_d = a + b(|T|)^3 \quad (3)$$

When the cyclic times increase, the value of C_d decreases a little, and the value of φ_d augments slightly; At the same cyclic times, C_d and φ_d increase remarkably with the reducing of temperature; Under certain cyclic times, the dynamic cohesion of frozen soil goes up clearly with temperature decrease. However, when temperature is below -5℃, this change becomes negligible. Thus, at the same temperature, dynamic shear strength decreases when dynamic loading continues, i.e, cyclic times increase. But it increases with temperature decreasing or confining pressure increasing, and especially at the dramatic water-ice phase change temperature range, it increases more obviously.

3 EFFECT OF TEMPERATURE ON GROUND MOTION PARAMETERS OF PERMAFROST SITES

Four typical frozen soil profiles along the Qinghai-Tibet railway in construction, kindly provided by Yunsheng Wu, Chief Engineer of the First Railway Design Institute of Ministry of Railway, China, are selected based on site exploration, wave velocity testing, borehole data and laboratory tests to carry out study on the effect of temperature on seismic ground motion parameters on frozen soil sites.

3.1 *Inputting artificial seismic waves*

Using criteria such as seismic ground motion intensity, thickness of frozen soil and historical earthquake data, artificial seismic waves respectively with exceedance probabilities of 63.5%, 10% and 2% in 50 years are used as inputting seismic ground motion, the characteristics of which are shown in Table1. Seismic response analysis with different exceedance probabilities were carried out to predict the maximum displacement, velocity and acceleration of ground motion under the effect of earth temperature, which leads to evaluate characteristics of seismic ground motion of frozen soil sites.

Table 1: The characteristics of the used artificial seismic waves

Ground motion Parameters	Exceedance in 50 years		
	63.5%	10%	2%
PGA on bedrock (gal)	26.0	-167.0	-326.0
Duration time (s)	40.96	40.96	40.96
Predominant period (s)	0.35	0.20	0.15

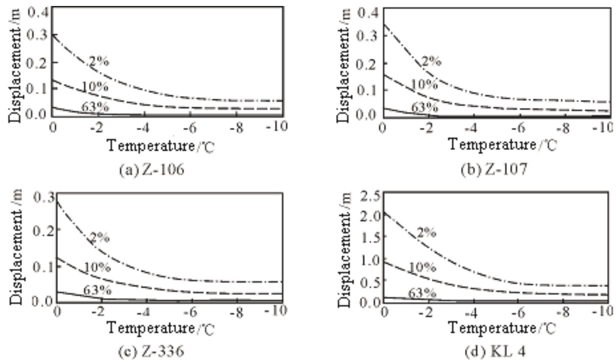

Figure 4. The curve of ground displacement at the four borehole profiles under different temperature

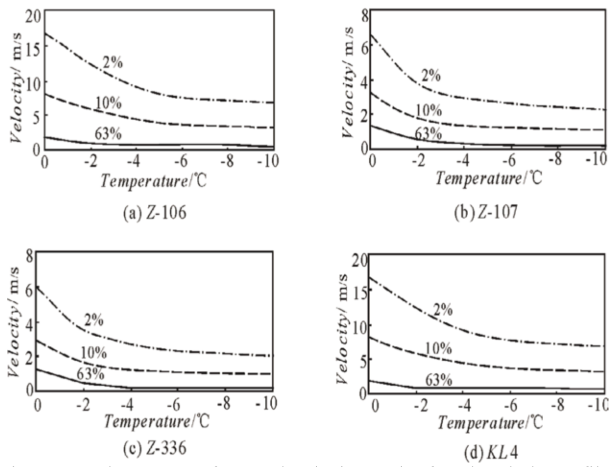

Figure 5. The curves of ground velocity at the four borehole profiles under different temperatures

3.2 *Effect of earth temperature on seismic ground motion parameters of permafrost site*

3.2.1 *The effect of earth temperature on displacement and velocity*

Fig.4 and Fig.5 show that the changes of displacement and velocity with earth temperature under seismic ground motion with different exceedance probabilities within 50 years. Obviously, both displacement and velocity decrease with the decrease of earth temperature for the four sites. This is because the cementation of ice is strengthened at lower temperature and the elastic modulus and strength of permafrost increase, consequently, shear wave velocity becomes high and as a result, the displacement and velocity on frozen soil site under the effect of earthquake decrease. But when temperature is below -5Cº, there would be no significant change of displacement and velocity. Earth temperature is no longer a major factor that affects the displacement and velocity of frozen soil.

3.2.2 *Effect of earth temperature on acceleration*

The effect of earth temperature on acceleration of ground motion on frozen soil sites is quite different from that on displacement and velocity (Fig.6). The change of acceleration with the decrease of temperature follows a pattern of decrease-increase-decrease again and then tending to stable. When the earth temperature is above -2Cº, acceleration of frozen soil sites decreases with the decrease of earth temperature. This is because the ice cementation is strengthened which leads to better seismic resistance of frozen soil. In temperature range -2Cº~-5Cº, acceleration increases significantly, which is more significant for stronger inputting ground motion. Since this temperature is within water-ice phrase, the dramatic phrase change and the variation of non-linear behavior of frozen soil in this state may cause this phenomenon. When earth temperature is below -5Cº the ground motion acceleration on frozen soil sites decreases with the decrease of earth temperature, which is less significant and largely stays stable in a narrow range. This shows that earth temperature is no more a major factor affects the ground motion on frozen soil sites, which coincides with the physical and mechanic properties of frozen soil and laboratory study results.

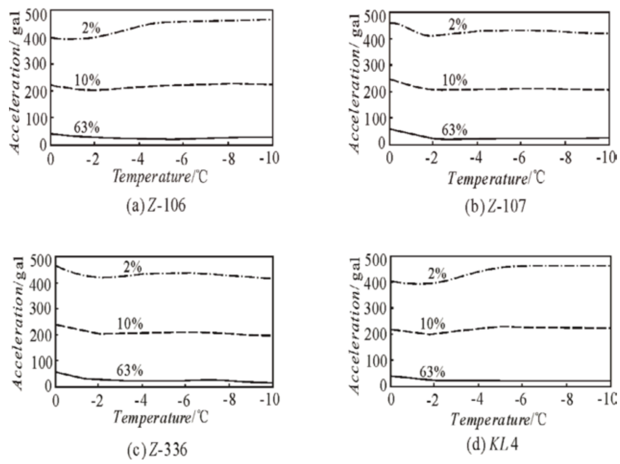

Figure 6. The curves of ground acceleration at the four borehole profiles under different temperatures

3.2.3 *Effect of earth temperature on β(T) spectrum on frozen soil sites*

Normalized acceleration response spectrum β(T) is the function of characteristic period, which varies according to seismic magnitude, distance to epicenter and deformation of site soil under the effect of earthquakes. Under seismic ground motion with a certain exceedance probability, the value of β and characteristic period (T_g) decrease with the decrease of earth temperature.

3.2.4 *Effect of earth temperature on predominant period on frozen soil sites*

Table 2 shows that the predominant period on frozen soil sites becomes predominantly shorter with the decrease of earth temperature. So the change of earth temperature also changes the frequency response characteristics of frozen soil. However, when earth temperature is below -5Cº, the decrease of predominant period is not very significant and the effect of temperature can be ignored. This is a similar situation for the effect of temperature on displacement, velocity and acceleration.

Table 2: The predominant periods of borehole profile under different temperatures

Borehole	Predominant period(s)			
	0~-2℃	-2~-5℃	-5~-7℃	-7~-10℃
Z-106	0.1406	0.1083	0.0721	0.0619
Z-107	0.1521	0.1035	0.0694	0.0596
Z-336	0.1423	0.1001	0.067	0.0575
KL4	0.3559	0.3114	0.2088	0.1793

4 CONCLUSIONS

Earth temperature has a significant effect on dynamic constitutive model, dynamic modulus and dynamic strength of frozen soil. In the water-ice phrase change, in which temperature ranges from 0 to -5C°, the effect of earth temperature is more significant, which can be disastrous.

Seismic response analysis on the measured profile of permafrost shows that the displacement, velocity of ground motion on frozen soil sites decreased with the decrease of earth temperature. However, the acceleration follows a pattern of decrease-increase-decrease again and then becomes stable with the decrease of earth temperature. The results provided by this study can be used for seismic design of structures on frozen soil sites.

ACKNOWLEDGEMENT

This research project is financially supported by the Headquarters of Qinghai-Tibet Railway Construction. The authors appreciate its significant contributions to scientific research on frozen soil.

REFERENCES

Qian J.H, Yin Z.Z, 1996, Theory on Geotechnical engineering and Methods for Calculation, Beijing: Hydraulic electricity Press.

Ma W., Wu Z.W, 1995, The electronic microscope analysis on microstructure of frozen sand, Journal of Glacier and Frozen Soil, Vol. 17 (No.2): 152~157.

Tong B.L, Li S.D, 1983, Some issues on the frozen soil in Qinghai-Tibet Plateau and their influential factors, Paper Collection on Study of Frozen Soil in Qinghai-Tibet Plateau, Beijing: Press of Science.

Wang S.L., 1996, Degeneration of frozen soil and environment problems of frozen soil, the 5th Chinese National Conference on Glacier and Frozen soil (Vol.1), 11~17, Lanzhou: Gansu Cultural Press.

Wang G.S, Jin H.J, Lin Q, 1996, natural and geotechnical engineering environment change along the Qinghai-Tibet Highway, the 5th Chinese National Conference on Glacier and Frozen soil (Volume 1), 43~50, Lanzhou: Gansu Cultural Press.

Wu Z.J, Wang L.M, Ma W. et al, 2003, Laboratory study on the constitutive model of frozen soil under seismic loading, Northwestern Journal of Seismology, Vol. 25 (No.2), 80~84.